431

High-quantum-efficiency Er^{3+} fiber lasers pumped at 980 nm

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Significant improvements in the operation of Er^{3+}-doped silica fiber lasers operating at wavelengths between 1.5 and 1.6 μm are reported. The use of 980 nm as the pump wavelength provides an output that is limited mainly by the quantum efficiency of the lasing process. It is thus considerably more efficient than previous results using ~810-nm pumping, where excited-state absorption degrades the lasing performance. Operation at three discrete output wavelengths is observed and is accounted for by studying gain across the lasing bandwidth.

A recent report[1] demonstrated that the most efficient wavelength with which to pump the Er^{3+} fiber laser system is 980 nm. To date, ~810 nm has been the preferred wavelength of the many pump bands possible for the Er^{3+} fiber laser,[2,3] this choice having been dictated by the availability of laser diodes operating at this wavelength. However, the 800-nm pump band of Er^{3+} suffers from the serious disadvantage of pump excited-state absorption[4] (ESA). Attempts have been made to overcome this by codoping the fiber with Yb^{3+} (Refs. 5–7) so as to use energy transfer from the Yb^{3+} to the Er^{3+} ions. Unfortunately, the overall efficiency of this codoped system is no better than that for a single-doped Er^{3+} laser when pumped at ~810 nm (with ESA present); this is due to the inefficiency of the energy-transfer process. Codoping does, however, relax the tolerance on the usable pump wavelength.[6] In contrast, the 980-nm absorption band does not suffer from ESA and is stronger than the 800-nm band. Furthermore, laser diodes operating at 980 nm seem to be a realistic proposition,[8] and their development will, as shown here, enable the production of a particularly useful class of efficient fiber lasers.

One fiber was used throughout this study and was fabricated using the solution doping technique,[9] with a concentration of Er^{3+} in the core of 0.08 wt. %. In addition, Al_2O_3 (3 wt. %) and P_2O_5 (3–4 wt. %) were added to the core to ensure an even distribution of Er^{3+} ions.[10] The fiber had a N.A. of 0.15 and was designed with a cutoff wavelength at 950 nm, thus ensuring single-mode operation at both pump and lasing wavelengths. Pump light at 980 nm was provided by an Ar^+/Styryl 13 dye laser combination.

Fiber lasers were constructed by butting cleaved fiber ends up against plane dielectric mirrors.[2] The mirror at the input end had a reflectivity of >99.8% over the 1.5–1.6-μm range while transmitting >90% of the pump light. Since Er^{3+} is a three-level laser, an optimum fiber length exists at which the available pump power (~20 mW) just bleaches the ground-state absorption; this length was found to be ~1 m.

The Er^{3+} fiber laser was observed to lase in three discrete wavelength ranges: 1.53, 1.56–1.57, and 1.60 μm. The different lasing wavelengths were obtained by altering the cavity output coupling (output mirror reflectivity), although a similar effect is observed by varying the fiber length.[2,6,11] Sample lasing characteristics are shown in Fig. 1, where output coupling has been chosen to demonstrate the three operating wavelengths. The lasing wavelength did not depend on the pump power, and the lasing bandwidth was typically 2 nm at a pump level of three times the threshold value.

The discrete nature of the operating wavelengths is a feature of Er^{3+} fiber lasers fabricated from silica and containing Al_2O_3 and P_2O_5.[6,12] The present result should be compared with the continuous range of wavelengths available when the fiber core contains only silica and GeO_2.[2,11] For the purposes of making a practical laser, the discrete operating wavelengths are an advantage since operation at a given wavelength can be assured for a reasonable range of device parameters.

Although the ground- and excited-state energy levels are composed of many Stark components, observation of three discrete lasing wavelengths indicates that the lasing action is dominated by a small number of them. The simplest scheme involves four energy levels, two in each of the ground and excited states. By

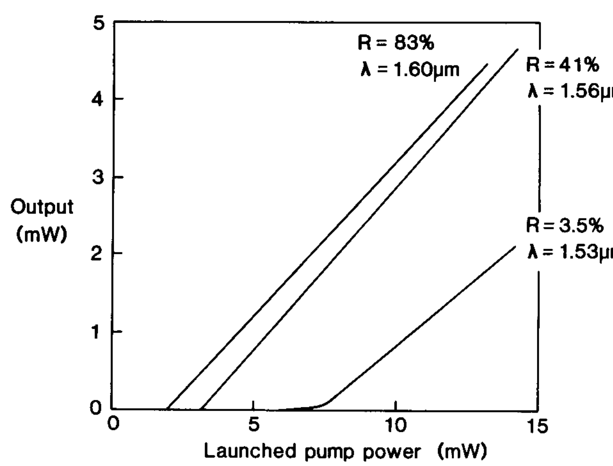

Fig. 1. Lasing characteristics for Er^{3+} fiber lasers pumped at 980 nm. The fiber length was 0.9 m, and the output coupler had reflectivities of 83% at 1.60 μm, 41% at 1.56 μm, and 3.5% at 1.53 μm.

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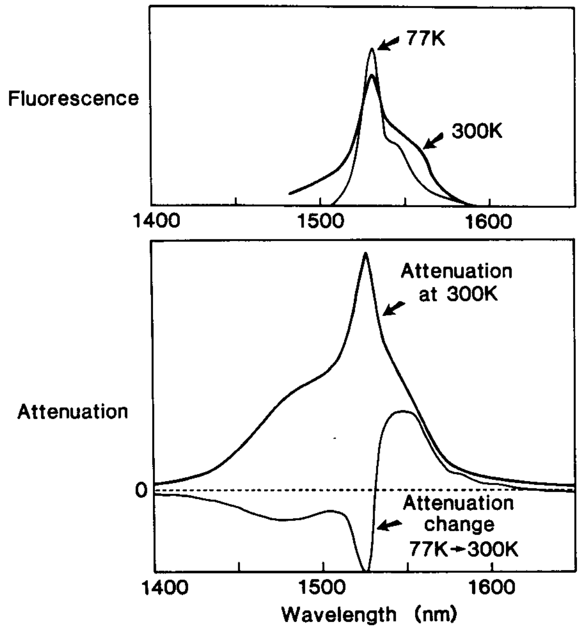

Fig. 2. Fluorescence and attenuation data at 77 and 300 K (not to scale). Attenuation at 300 K is shown with the change observed in going from 77 to 300 K.

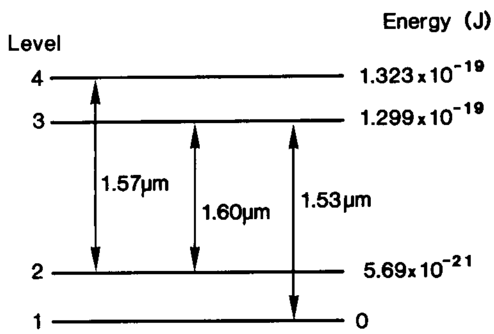

Fig. 3. Energy-level scheme for Er^{3+} in a silica fiber codoped with Al_2O_3 and P_2O_5.

examining both fluorescence and absorption measurements made at 77 and 300 K (Fig. 2), it is possible to assign the three lasing transitions among the various levels; this is done in Fig. 3. The remaining possible transition (at 1.50 μm) is not expected since it terminates on the same level as the 1.53-μm transition but has a lower gain, as shown below (see Fig. 5).

The fiber will be bleached at a particular wavelength when the population of the relevant levels is equal. The fractional inversion (i.e., of the two upper levels with respect to the total population) required to bleach the three different transitions may be calculated at 300 K with the aid of Boltzmann statistics; they are found to have a ratio of 2.3:1.5:1 in order of increasing wavelength.

To test this prediction experimentally the gain across the lasing bandwidth was measured using the arrangement shown in Fig. 4. A dichroic coupler allowed the launched pump power and the gain/loss to be measured simultaneously. The results are shown in Fig. 5, where it can be seen that at low pump powers the only wavelength at which gain exceeds loss is 1.61 μm. On increasing the pump power, gain at 1.565 μm becomes greater, with a small dip in the gain between these two wavelengths. At still higher pump powers gain at 1.53 μm rapidly becomes dominant, again with a dip between this and the previous wavelength. This behavior is consistent with the energy-level scheme of Fig. 3 and (noting that the emission cross section increases from 1.6 to 1.53 μm) accounts for the different lasing wavelengths.

The gains for the three different wavelengths as a function of pump power (derived from Fig. 5) are shown in Fig. 6. We can now see that as the output coupling is increased (greater cavity loss), lasing will occur first at 1.6 μm, then at 1.56 μm, and finally at 1.53 μm, just as observed. Furthermore, the ratio of the pump powers required to bleach the fiber at the three wavelengths is 2.3:1.4:1, in good agreement with that predicted.

Reexamining the laser characteristics of Fig. 1, we find the launched (absorbed) slope efficiencies to be 35% (65%) at 1.53 μm, 46% (58%) at 1.56 μm, and 44% (51%) at 1.60 μm. The slope efficiency with respect to the launched power, δ, and the quantum efficiency, QE, are related through

$$\delta = P_a\left(\frac{T}{T+L}\right)\frac{h\nu_L}{h\nu_p}\,\eta\mathrm{QE},$$

where P_a is the fraction of the pump power absorbed (determined experimentally), T is the transmission of

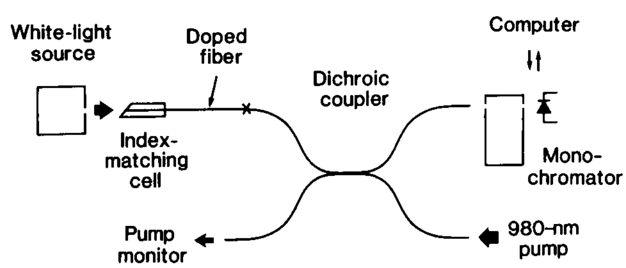

Fig. 4. Experimental arrangement used to measure the small-signal gain as a function of the wavelength.

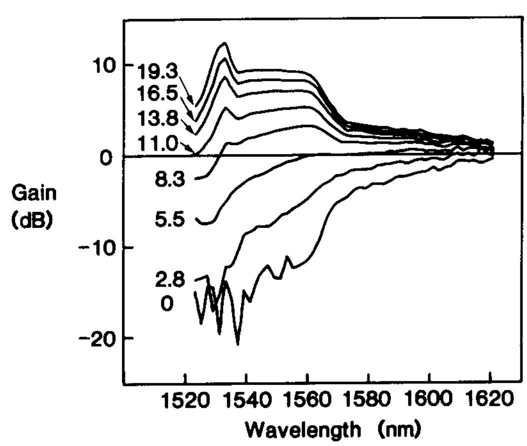

Fig. 5. Gain as a function of wavelength for various pump powers (in milliwatts). The fiber length was 1.3 m.

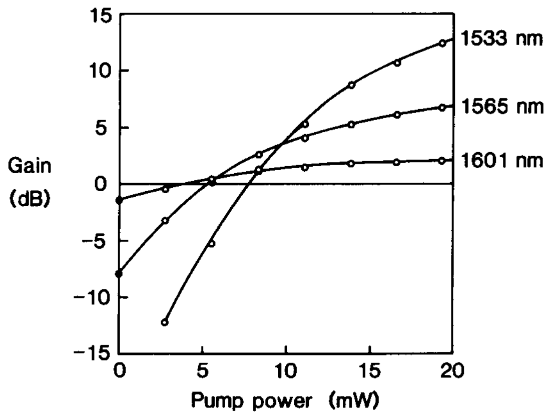

Fig. 6. Gain for the three lasing wavelengths as a function of the pump power.

the output coupler, L is the cavity loss other than output coupling (i.e., butt loss) assumed at 5%,[13] $h\nu_L/h\nu_p$ is the ratio of laser to pump photon energies, and η is the overlap between the signal and pump modes (found to be 0.98 using the method of Ref. 14).

With this definition the quantum efficiencies for the three laser wavelengths are found to be 1.09 ± 0.16, 1.01 ± 0.15, and 1.10 ± 0.18. A comparison of the results for lasing at 1.56 μm gives launched pump-power slope efficiencies of 46% for 980-nm pumping (this research), 16% for 806-nm diode array pumping,[13] and 17% for an Er^{3+}/Yb^{3} fiber laser pumped at 810 nm.[6]

This research clearly demonstrates the advantage of pumping at 980 nm for Er^{3+} fiber lasers. It is not unrealistic to expect 10 mW of power at 1.53, 1.56, or 1.60 μm from an Er^{3+} fiber laser pumped with a single-stripe 980-nm diode. Moreover the addition of line-narrowing elements to the cavity should allow single-longitudinal-mode operation,[15] making the laser an attractive source for coherent communications.

Recent reports[15,16] suggest that efficient pumping may also be obtained at 1.48–1.49 μm, a range available from laser diodes. Although amplifiers with useful gains have been made, lasers pumped at $\sim$1.48 μm have yet to show significant output powers.

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